

Assessing the performance of global MHD models using key system parameters and empirical relationships

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Annapolis, April 2016

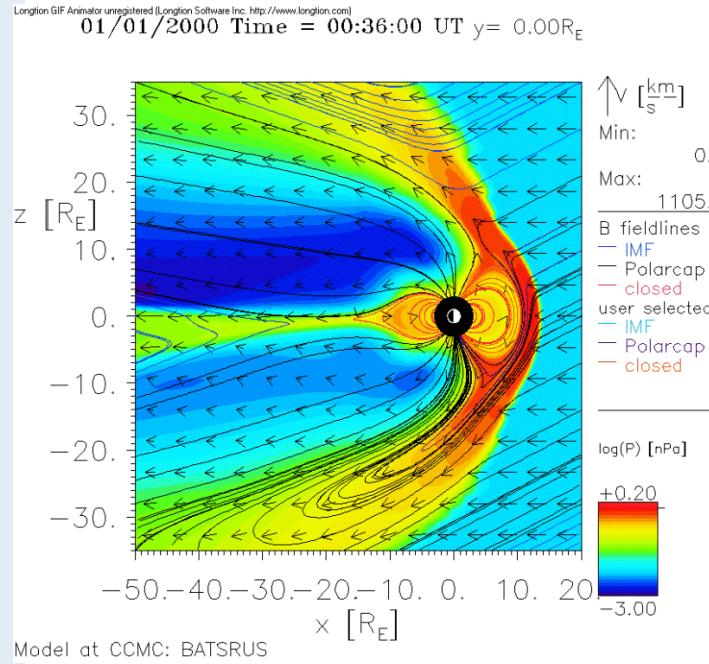
Global magnetohydrodynamic models

Setup & advantages

- ✓ First-principle based (MHD equations)
- ✓ Simple handling with initial/boundary conditions
 - > Solar wind as input, both real and artificial events
 - > No initial state required

provide

- ✓ 3-D , Dynamics
- ✓ Any parameter available at any point



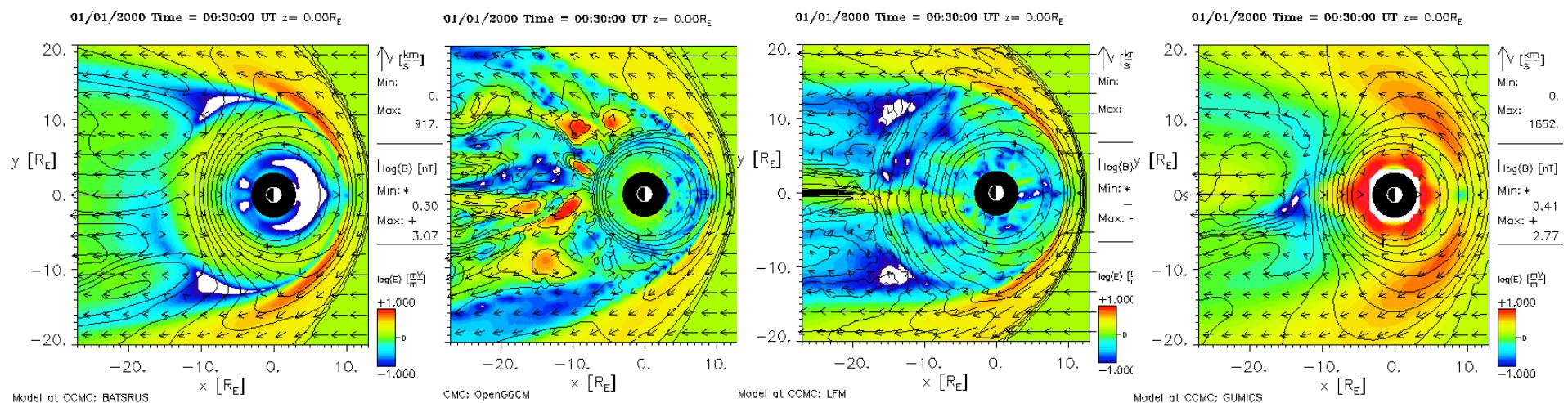
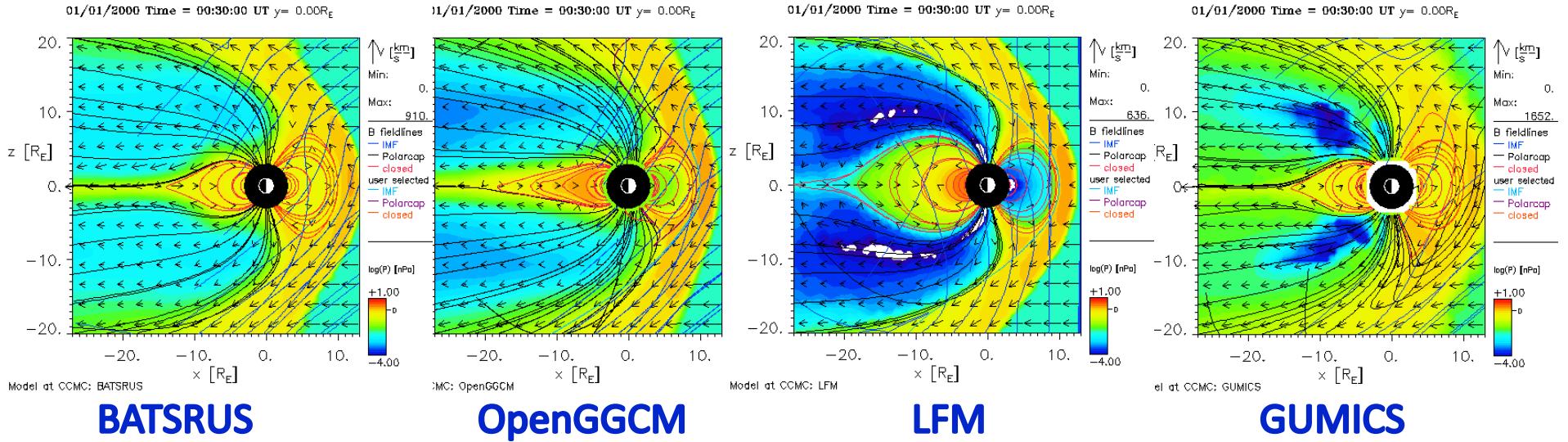
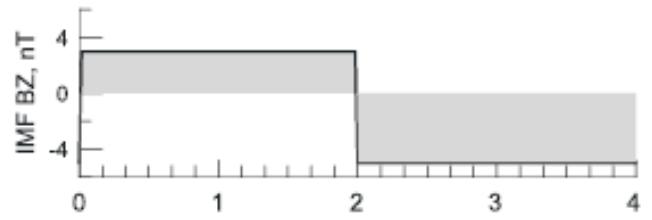
Strong need for validation & benchmarking between models also because fast development of global MHD models

- Users (accuracy?)
- Developers (assessment of improvements?)

Problems

- Reduced physics
- Use different numerical methods, grids, etc
- Strong numerical effects (depends on resolution, order of num scheme, etc.
→ reconnection??)
-
- Black box - like for users
- **Accuracy?**

Motivation



How to validate / compare GMHD models??

No obvious etalon (test solution) or procedure exists to test GMHD

(1) Compare to reality (real parameters for same input) quantitatively

- = adopt/prefer **statistical empirical dependencies**, rather than observations of individual s/c at specific trajectories;
- = interested in **parameter values** and **parameter variations** (IMF, Pd,...)

(2) Validate a set of **key system parameters** rather than some particular characteristics (KSP quantitatively the capability of global MHD models to represent the key global-scale magnetospheric characteristics related to:

- global state equilibria (\mathbf{R}_{MP} , \mathbf{P}_{PS} , \mathbf{B}_L)
- magnetosphere – ionosphere connection (total FAC - **TFAC**)
- global magnetospheric dynamics (convection $\Delta\Phi$, growth phase $\Delta\mathbf{B}_L/\Delta t$, ΔT)

(3) Avoid comparing what/where global MHD is known to perform bad (e.g. inner MSPH ...)

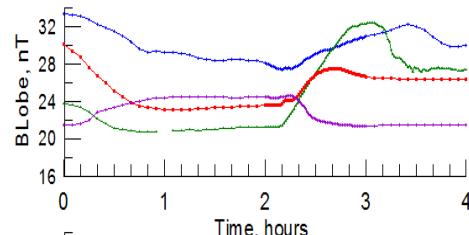
Show the first systematic evaluation of four first-principle-based global magnetospheric models – BATSRUS, LFM, GUMICS and Open GGCM;

Key magnetospheric system parameters

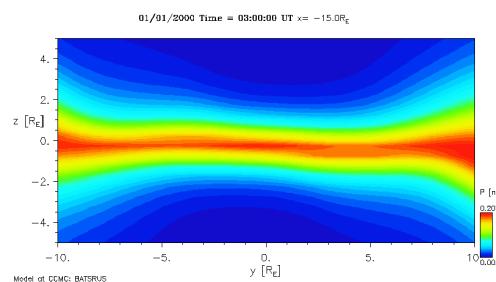
KMP = those parameters which:

- ✓ Characterize (responsible for) the global equilibria and dynamics of the system;
- ✓ Have a large (MHD)-scale;
- ✓ Are available from observations & can be computed from simulations

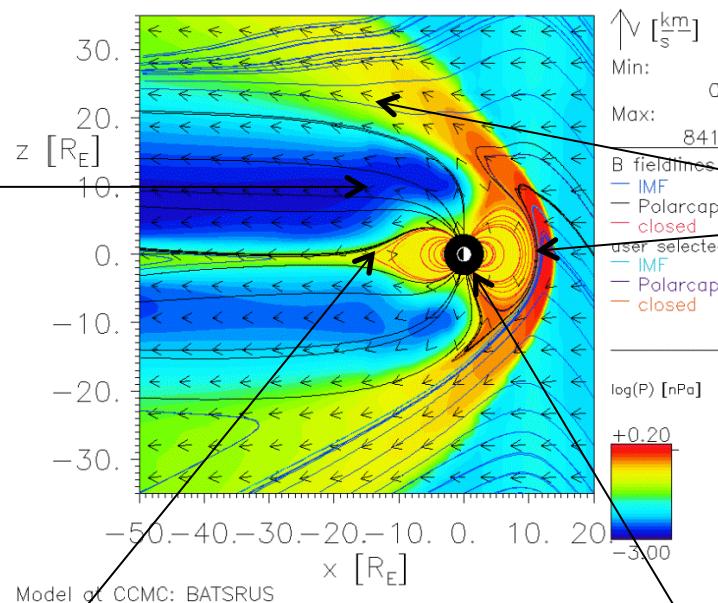
Lobe magnetic field



Plasma pressure
(central plasma sheet)

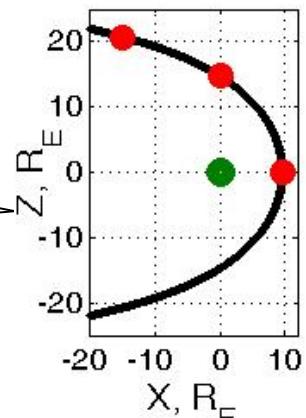


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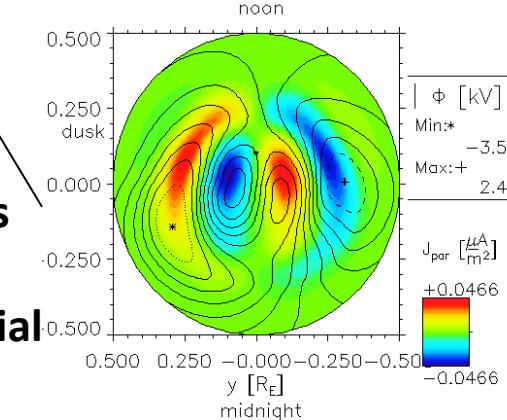


Model of CCMC: BATSRUS

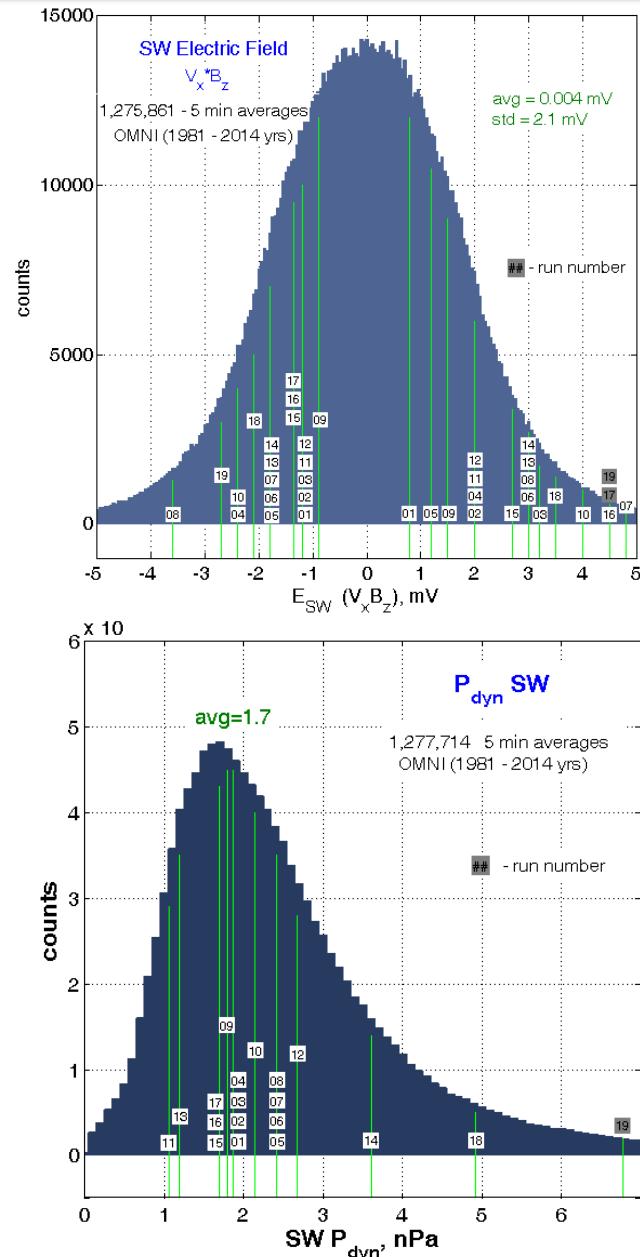
Magnetopause position



Field aligned currents
&
Cross polar cap potential



Input structure (data coverage)



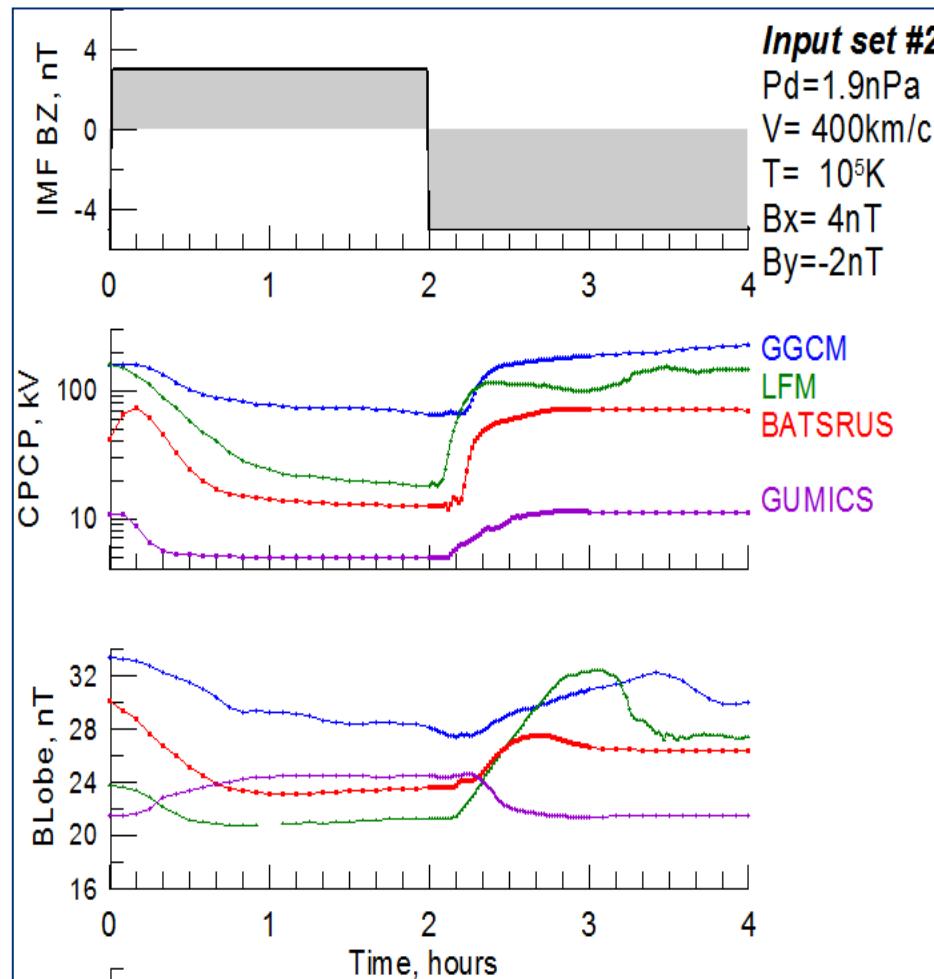
To construct the set of inputs, that cover the real distribution of SW parameters, we use the OMNI data base statistics for years 1981-2014.

The set of model inputs:

	$V_x, N, T,$ [km/s] [cm ⁻³] [K]	$B_x, B_y,$ [nT]	$(B_{z0}, B_{z1}, B_{z2}),$ [nT]	P_d [nPa]
01	-400, 7, 100k,	+4, -2,	(-5,+3,-2)	1.87
02	-400, 7, 100k,	+4, -2,	(-5,+3,-5)	1.87
03	-400, 7, 100k,	+4, -2,	(-5,+3,-8)	1.87
04	-400, 7, 100k,	+4, -2,	(-5,+6,-5)	1.87
05	-600, 4, 250k,	+4, -2,	(-5,+3,-2)	2.41
06	-600, 4, 250k,	+4, -2,	(-5,+3,-5)	2.41
07	-600, 4, 250k,	+4, -2,	(-5,+3,-8)	2.41
08	-600, 4, 250k,	+4, -2,	(-5,+6,-5)	2.41
09	-300, 12, 35k,	+4, -2,	(-5,+3,-5)	1.80
10	-800, 2, 350k,	+4, -2,	(-5,+3,-5)	2.14
11	-400, 4, 100k,	+4, -2,	(-5,+3,-5)	1.07
12	-400, 10, 100k,	+4, -2,	(-5,+3,-5)	2.68
13	-600, 2, 250k,	+4, -2,	(-5,+3,-5)	1.20
14	-600, 6, 250k,	+4, -2,	(-5,+3,-5)	3.61
15	-450, 5, 50k,	+4, (-2,-2,-8),	(-5,+3,-6)	1.69
16*	-450, 5, 50k,	+4, (-2,-2,-10),	(-5,+3,-10)	1.69
17*	-450, 5, 50k,	+4, (-2,-2,-16),	(-5,+3,-10)	1.69
18	-700, 6, 500k,	+4, -2,	(-5,+3,-5)	4.92
19	-900, 5, 500k,	+4, -2,	(-5,+3,-5)	6.77

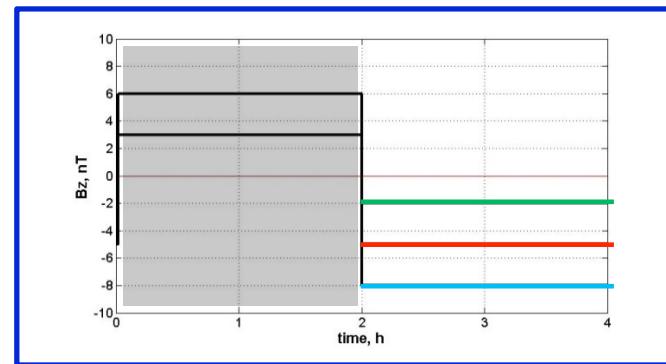
Simulations: 4 models X 19 inputs X 4 hour = 304 h

Input structure (dynamical response)



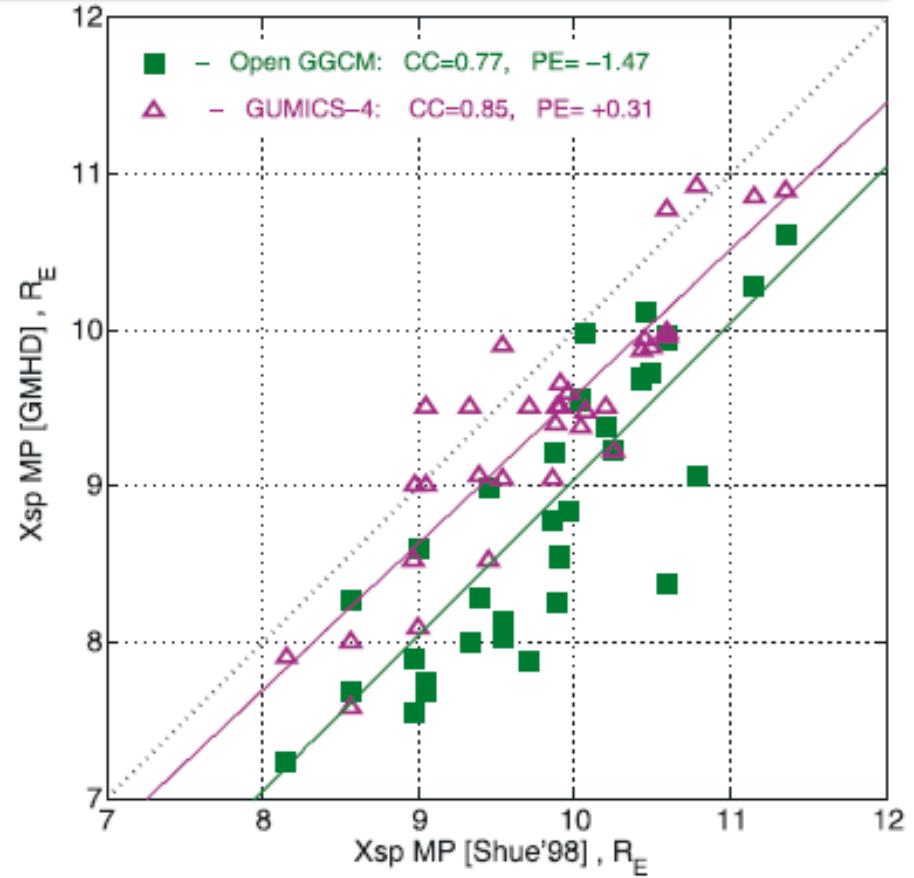
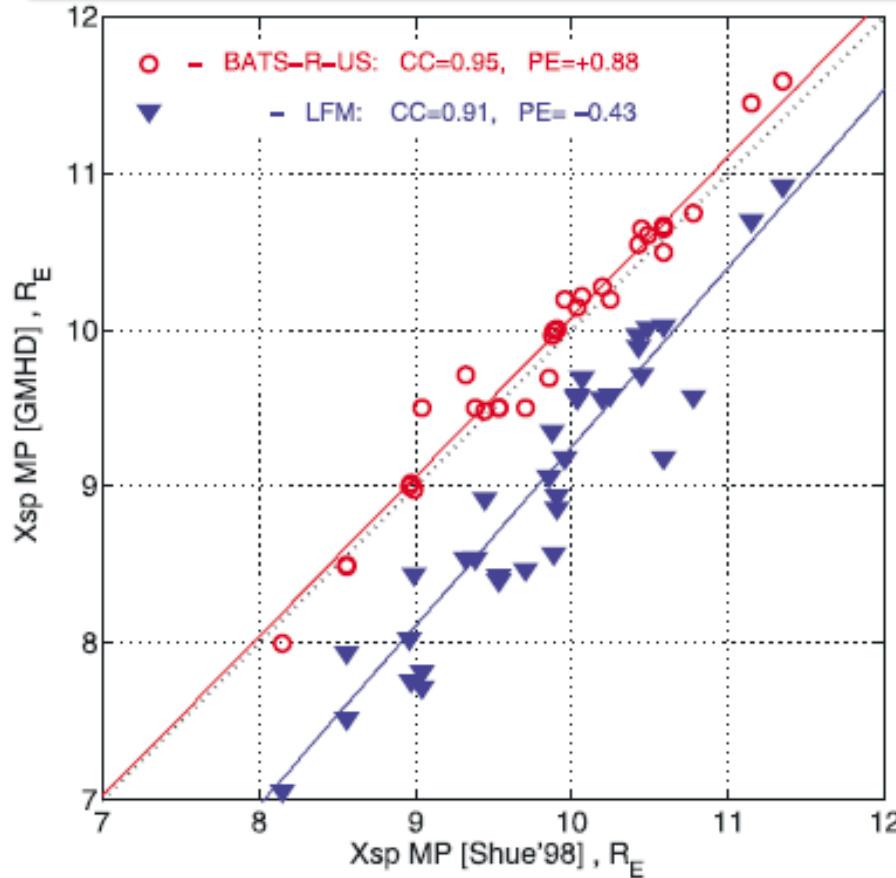
Variable IMF B_z (step-like change) input:

- 1) transient system response
- 2) simple input structure and clear system response



- **Pre-history – Southward IMF.**
- **First 2h interval – Northward IMF.**
Filling up the plasma sheet with SW plasma.
- **Next 2h interval – Southward IMF.**
Development of loading-unloading (substorm) cycle:
 - 1) same initial mgnspf state, but different loading rate
 - 2) different initial mgnspf state, but same loading rate

Results: magnetopause subsolar point



Empirical model for comparison -
Shue et al., JGR, 1998

- Best predicted by **BATS-R-US**
- Underestimated by:
~ 0.5 R_E in **GUMICS-4**
~ 1 R_E in **LFM** and **Open GGCM**

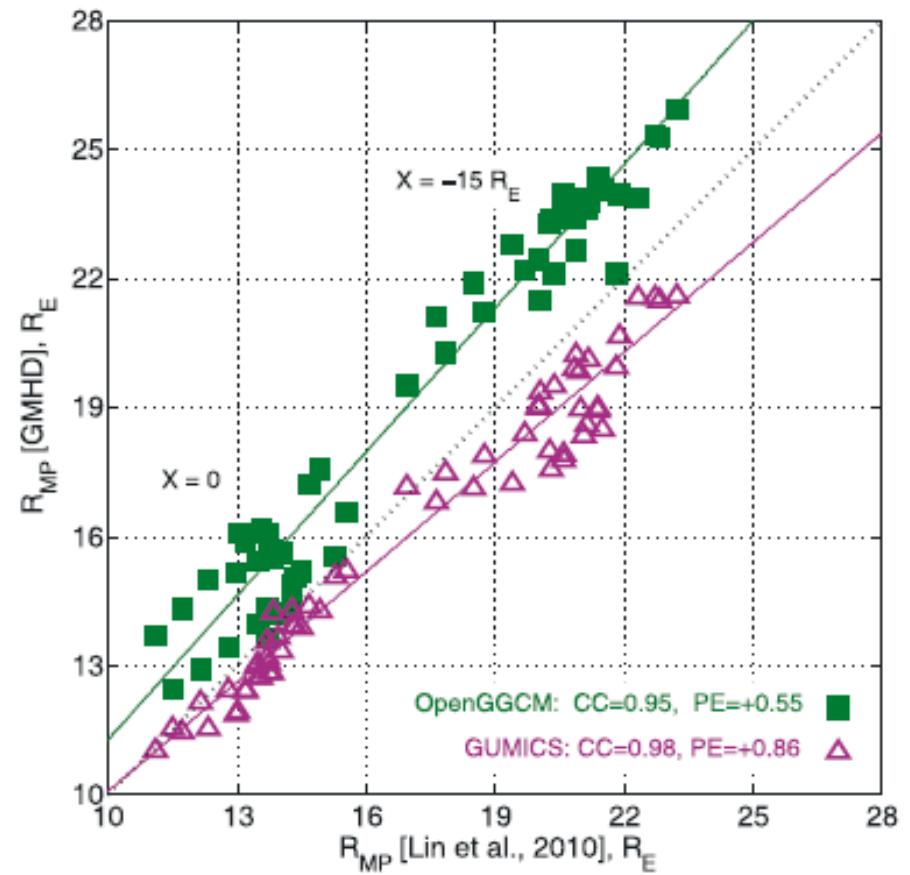
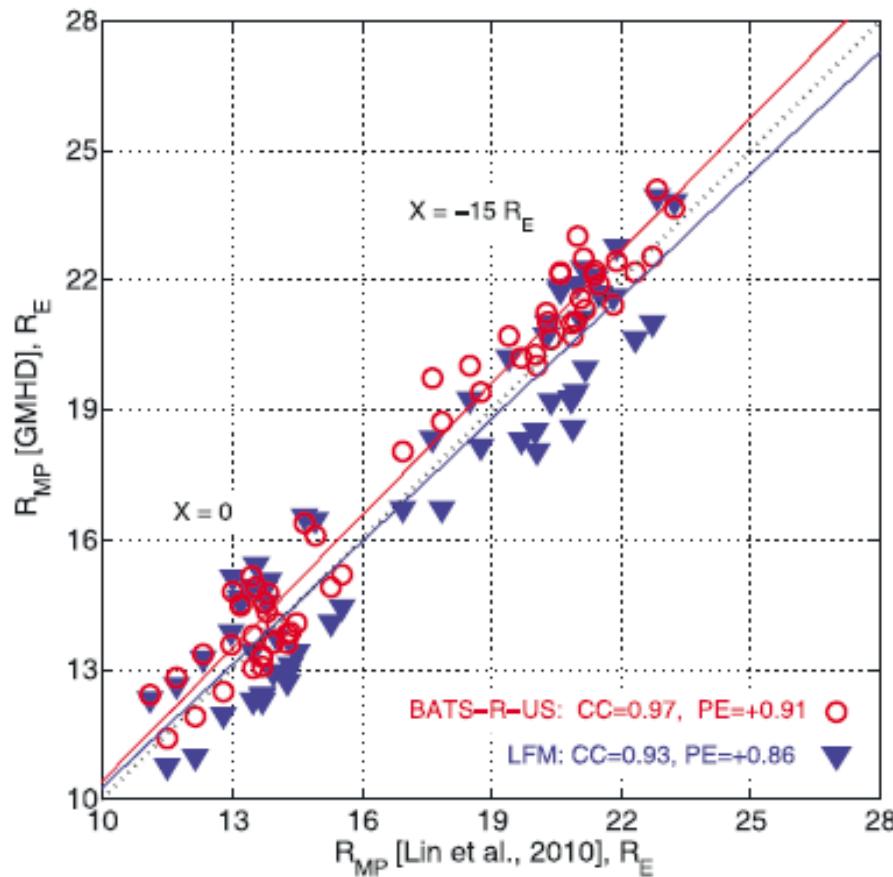
Used metrics:

- Linear correlation analysis: CC – cor. coef., standard deviation, slope.
- Prediction Efficiency:

$$PE = 1 - \frac{\langle (X_{obs} - X_{mod})^2 \rangle_i}{\sigma_{obs}^2}, \quad PE = 1 - \text{perfect}$$

$$PE = 0 - \text{relatively well}$$

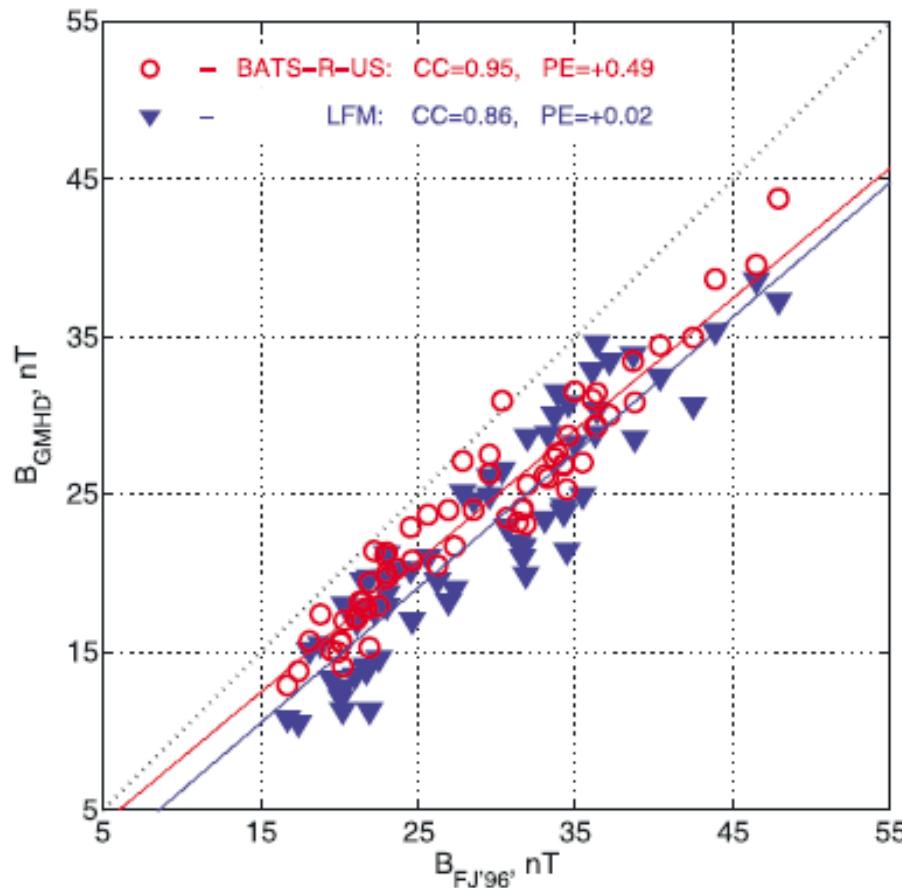
Tail magnetopause



Empirical model for comparison - Lin et al., JGR, 2010

- Best predicted by **BATS-R-US**
- **Open GGCM** overestimates by $\sim 2\text{-}3 R_E$

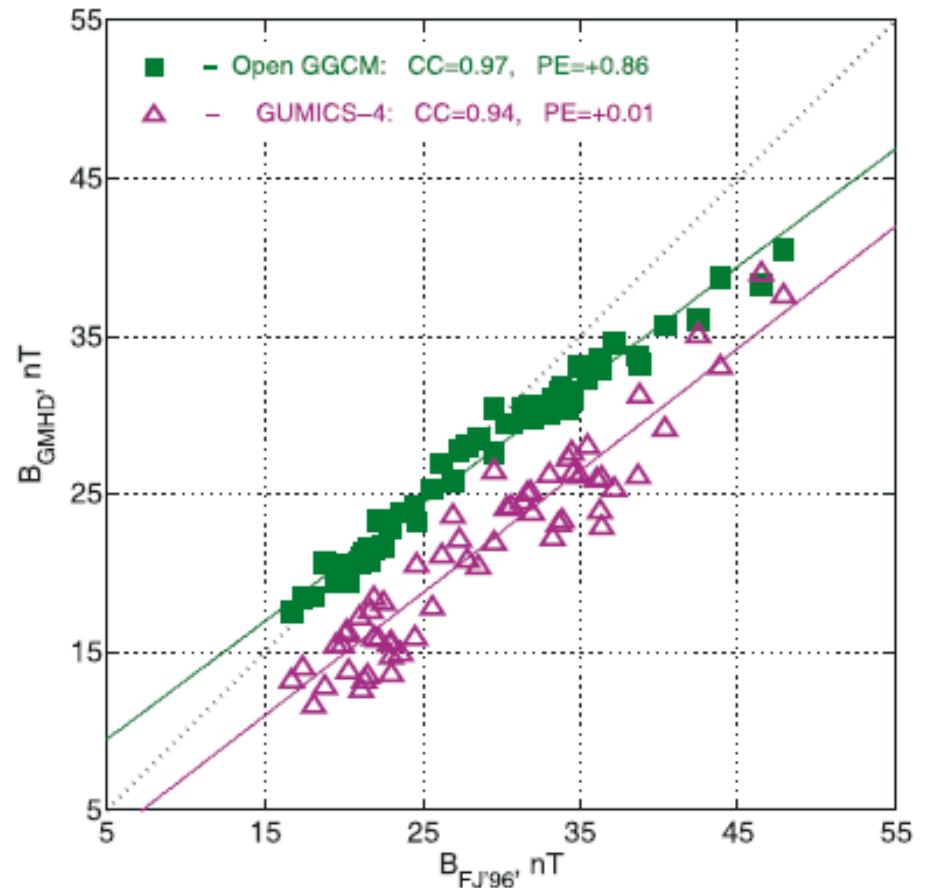
Magnetic field in tail lobes



Empirical model
Fairfield and Jones, JGR, 1996

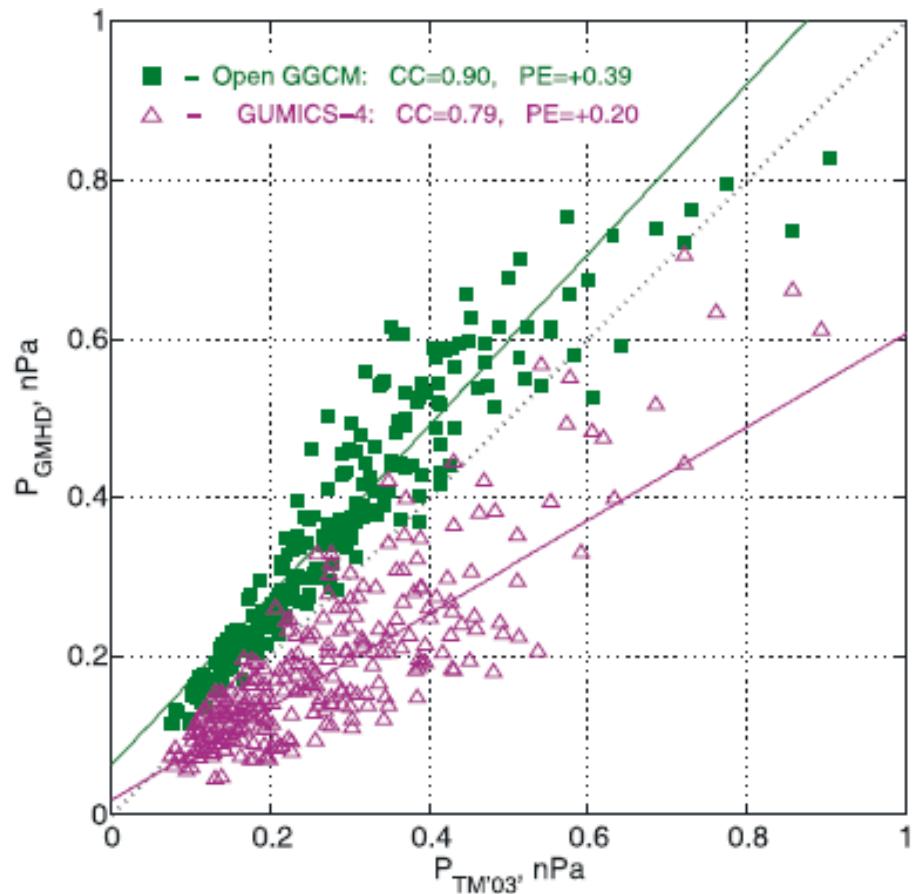
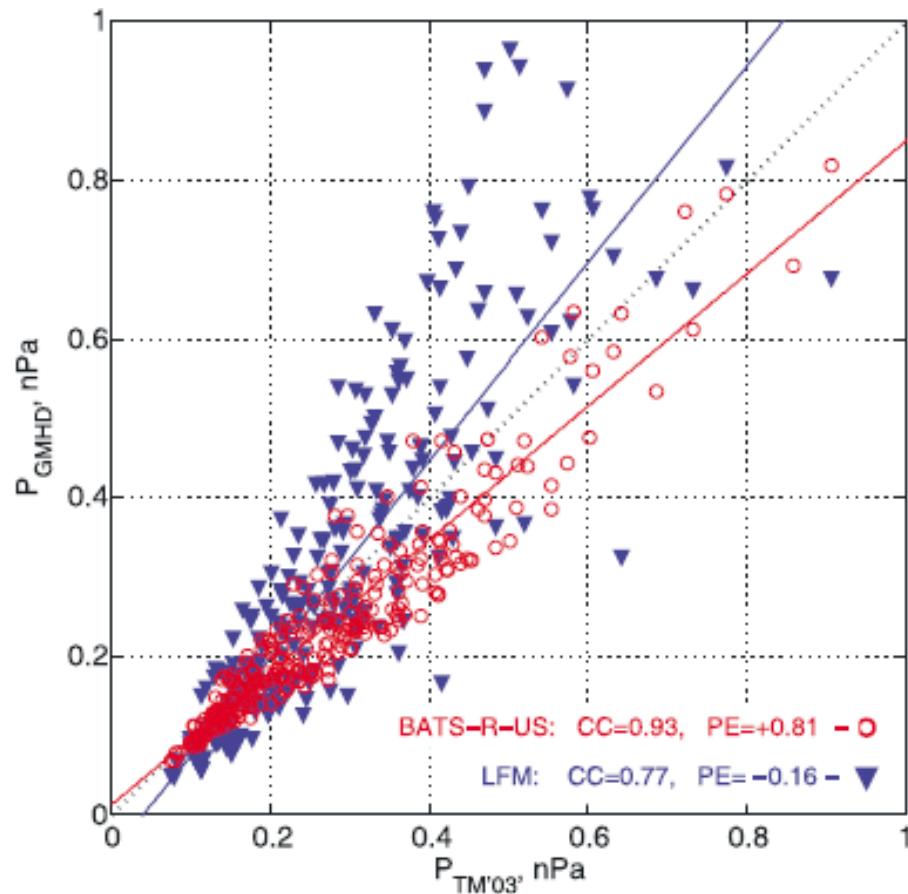
$X = -15 \text{ and } -25 R_E$

$Z = 8 R_E$



- Best predicted by **Open GGCM**
- Underestimated by:
 - ~ 20% in **BATS-R-US**
 - ~ 25% in **LFM**
 - ~ 30% in **GUMICS-4**

Plasma pressure in central plasma sheet



Empirical model

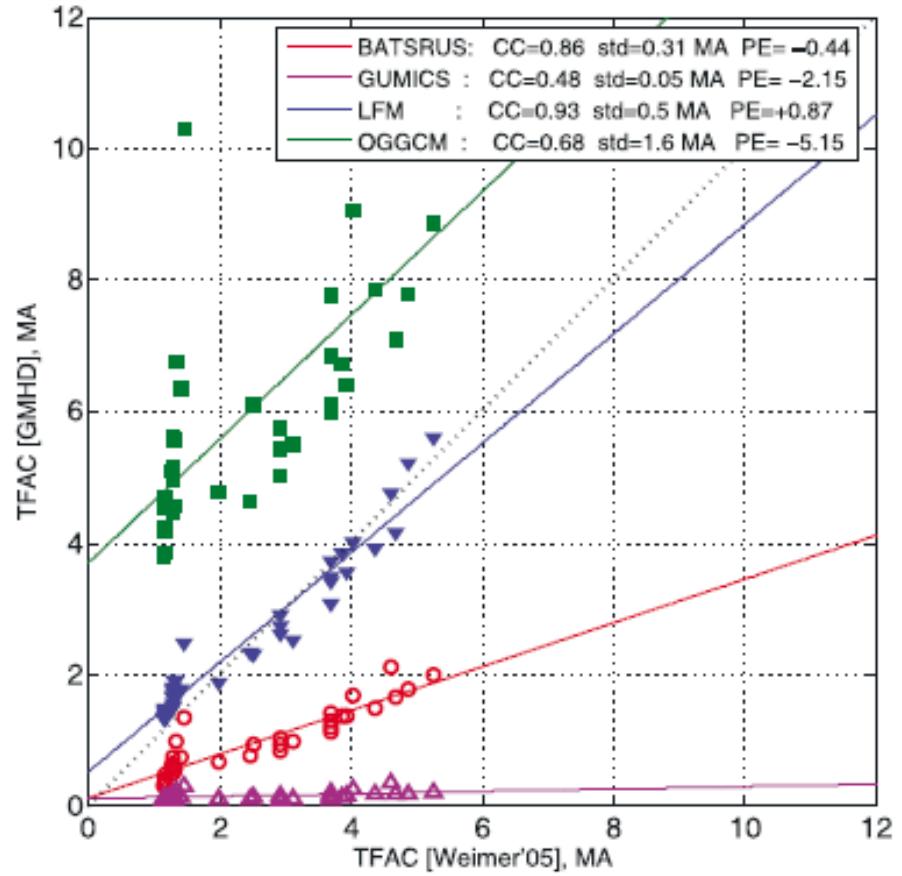
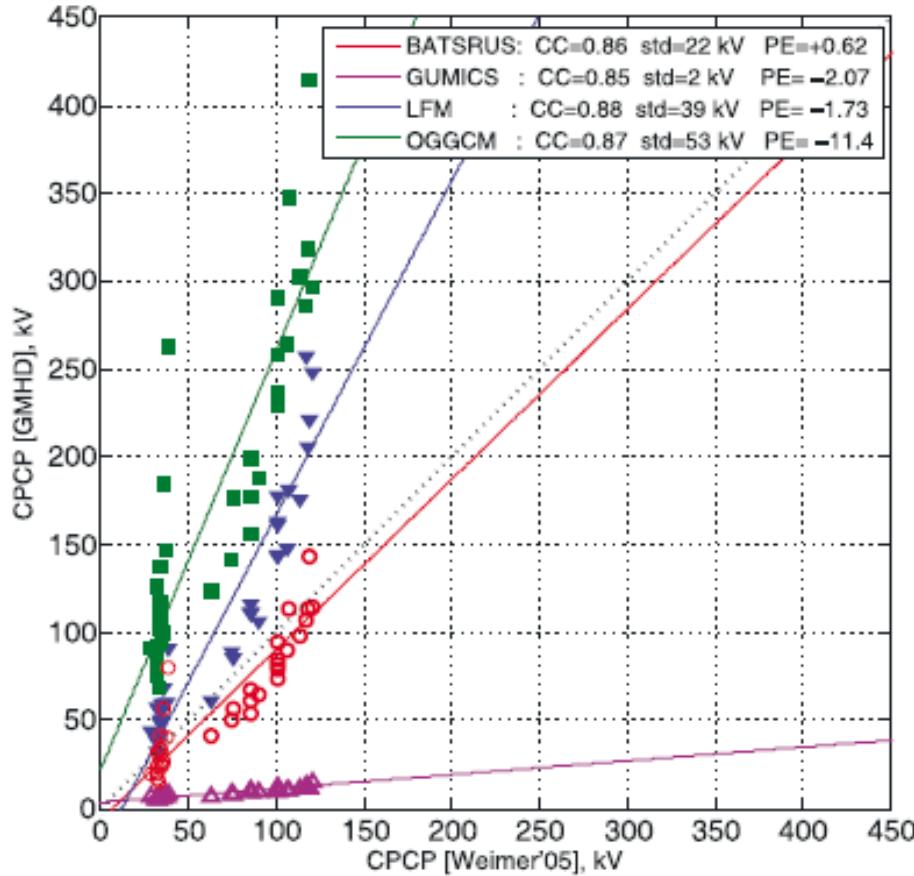
Tsyganenko and Mukai, JGR, 2003

$X = -12, -15, -20, -25 R_E$

$Y = 0, 10 R_E$

- All models better predict the P_p value in more distant tail
- Systematic difference between models

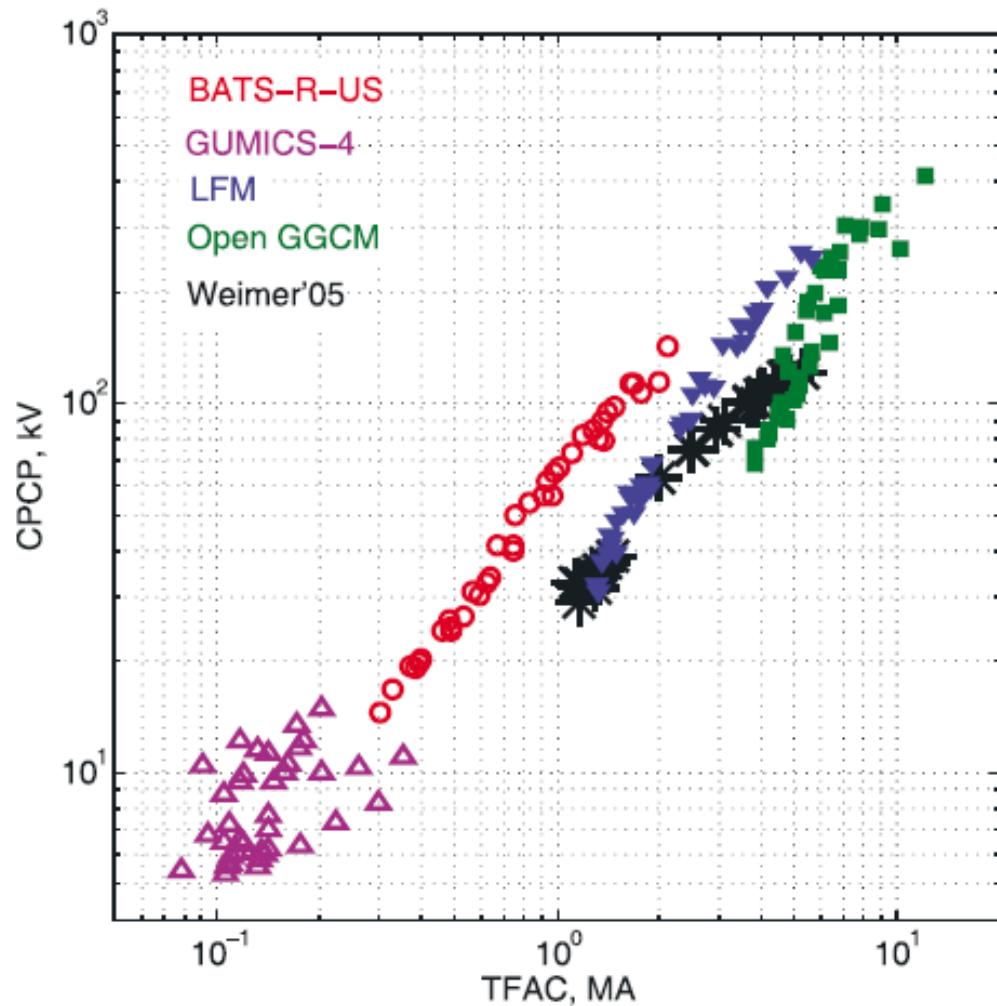
Ionospheric total FAC and cross polar cap potential



Empirical model **Weimer, JGR, 2005**

- Best predicted by **BATS-R-US**
- 1.5 times overestimated by **LFM**
- Highly underestimated by **GUMICS**
- 2-2.5 times overestimated by **Open GGCM**
- Best predicted by **LFM**
- 2 times underestimated by **BATS-R-US**
- Highly underestimated by **GUMICS**
- 2.5 times overestimated by **Open GGCM**

Ionospheric TFAC and CPCP (I-U relation)



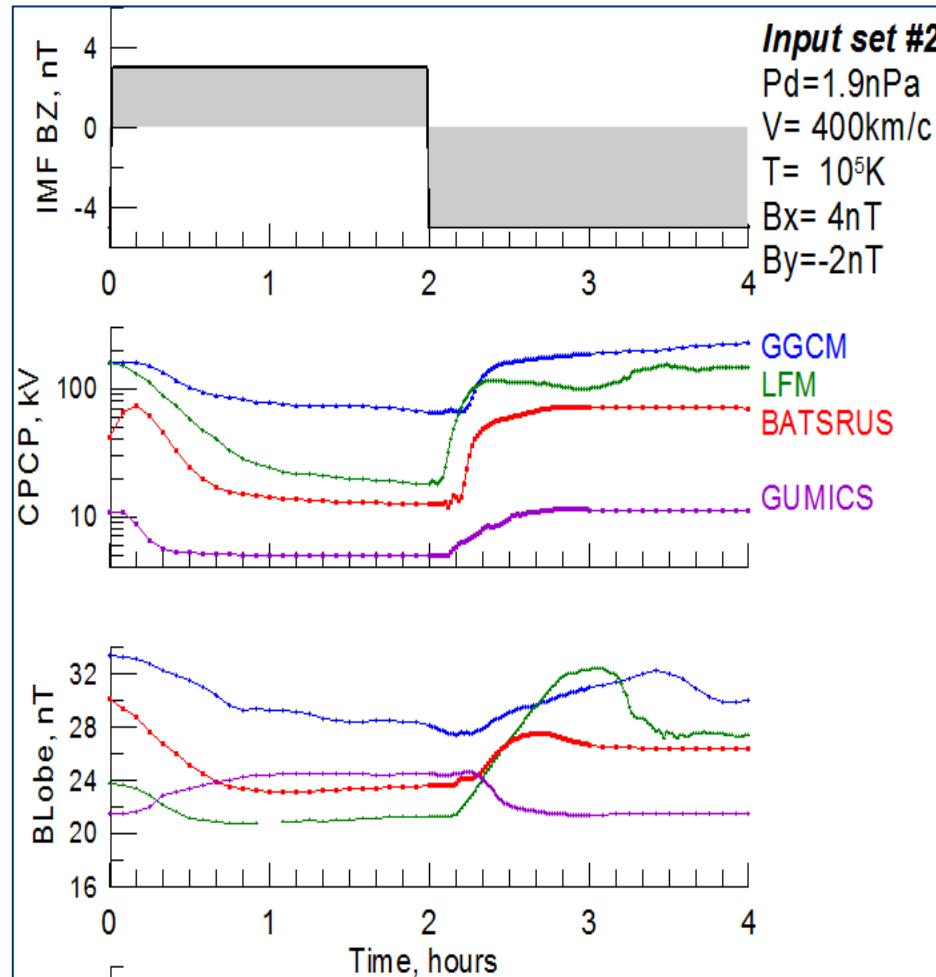
Empirical model
Weimer, JGR, 2005

All GMHD models – systematic deviation from empirical I-U relation

- LFM: right amount of TFAC, however ~1.5 times CPCP overshooting during SBz IMF.
- BATSRUS: right CPCP during SBz IMF, but ~2 times lower TFAC.
- GUMICS: very low CPCP and level of FACs generation.

Growth Phase

-- example: 4 GMHD time series



- Very different loading/unloading response of GMHD models,
- both in amplitude and variation

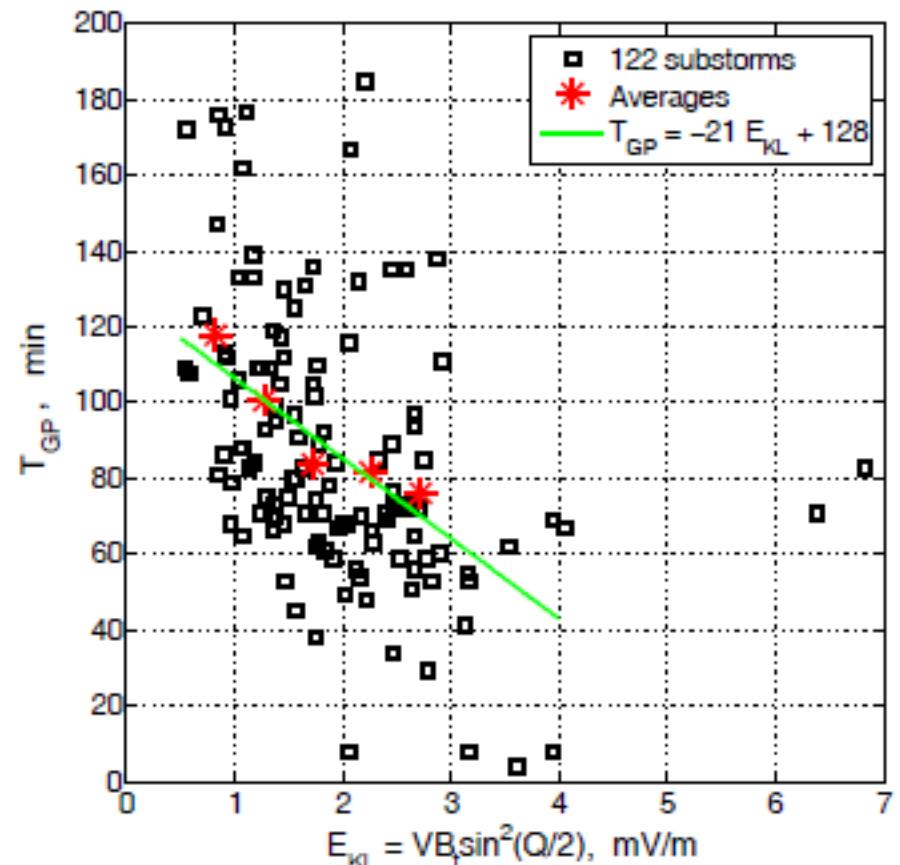
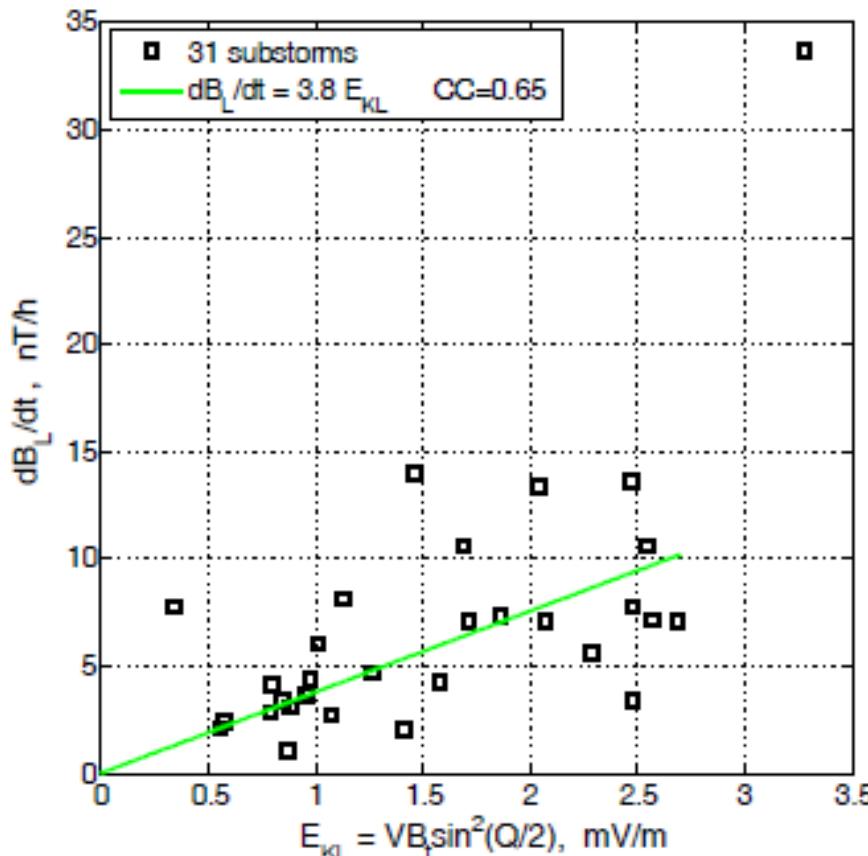
Growth phase empirical model (dB_L/dt & T_{GP})

2001-2014
OMNI data +
CLUSTER & Geotail
in tail lobes

Selection criterions

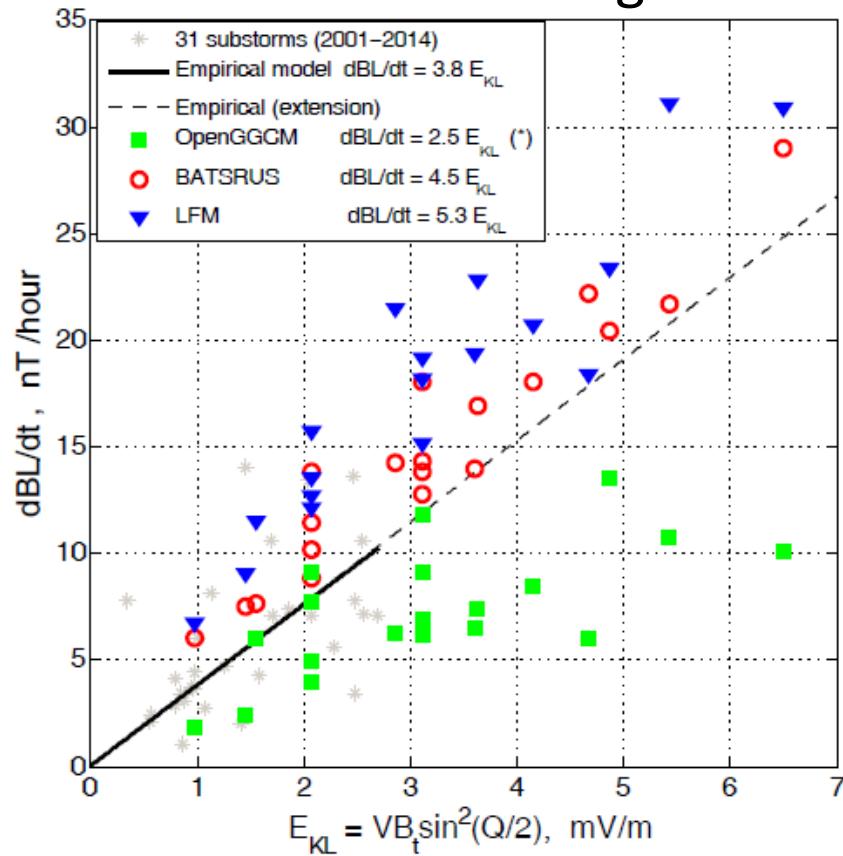
- t_1 using PC ($\delta PC \sim \delta E_{KL}$)
 - IMF $B_z^N > 0.5$ nT $t > 1.5$ h
 - IMF $B_z^S < -1$ nT $t > 1.5$ h
 - $|AL_{pre}| < 50$ nT

- t_2 using SML (SuperMAG)
 - Tai I s/c in lobes ($\beta > 1$)
 - Reduced to $X = -15R_E$ (FJ'96)
 - SW δP_{ram} considered (FJ'96)

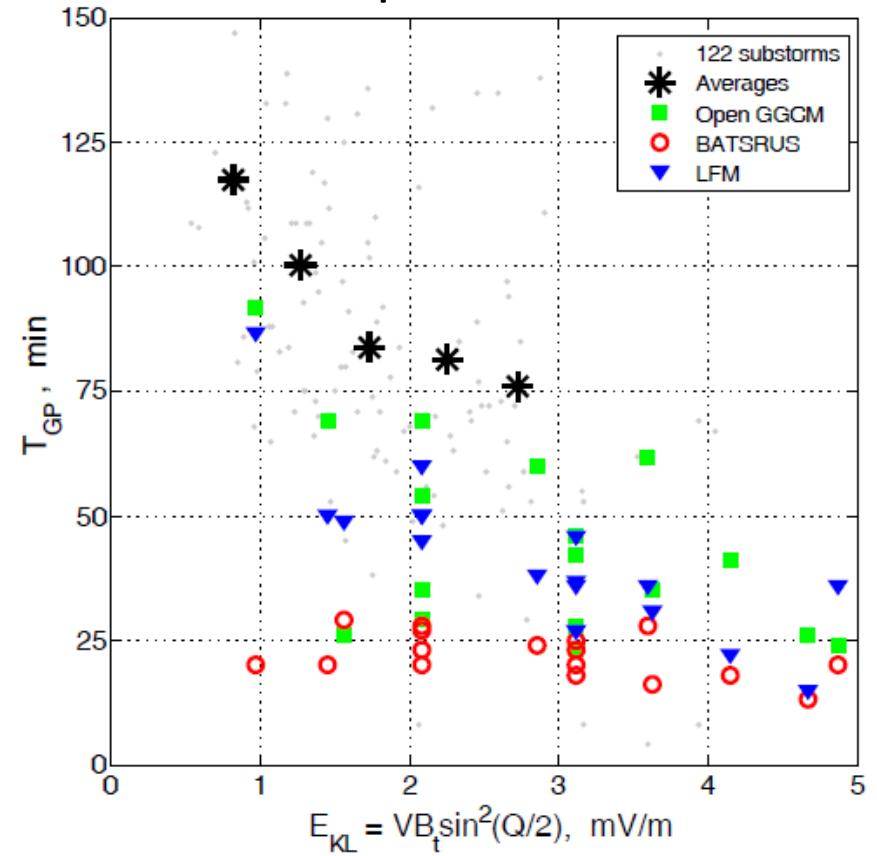


GMHD growth phase characteristics

Lobe field loading rate



Growth phase duration



LFM: ~40% higher

OpGGCM: ~30% lower, Saturation

BATSRUS: ~20% higher

LFM: ~25% shorter

OpGGCM: ~25% shorter

BATSRUS: 25 min. *Not sensitive to E_{KL}*

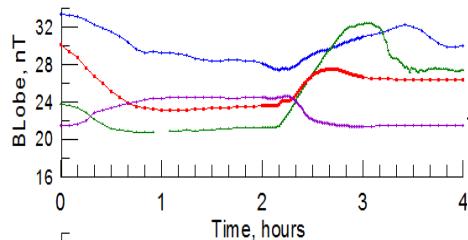
Summary of the skill scores of four GMHD models

	BATS-R-US	GUMICS	OpenGGCM	LFM
	slope /CC / PE	slope / CC / PE	slope / CC / PE	slope / CC / PE
R _S (subsolar)	1.01/0.95/+0.88	0.96/0.85/+0.31	0.90/0.77/-1.47	0.92/0.91/-0.43
R _T (terminator)	1.03/0.64/-0.02	0.97/0.93/+0.62	1.11/0.47/-3.20	1.00/0.44/-0.95
R _T (X=-15R _E)	1.03/0.77/+0.22	0.93/0.80/-0.55	1.13/0.73/-3.19	0.99/0.73/-0.04
B in Lobes	0.83/0.95/+0.49	0.75/0.94/+0.01	0.93/0.97/+0.86	0.78/0.86/+0.02
P _{PS}	0.87/0.93/+0.81	0.64/0.79/+0.20	1.26/0.90/+0.39	1.10/0.77/-0.16
GP Loading Rate	~ 1.20 dB _L /dt	No	~ 0.65 dB _L /dt	~ 1.40 dB _L /dt
GP Duration	Short, Not depend on E _{KL}	No	~ 0.75 T _{GP}	~ 0.75 T _{GP}
CPCP	0.89/0.86/+0.62	0.12/0.85/-2.07	2.62/0.87/-11.4	1.64/0.88/-1.73
Total FAC	0.37/0.86/-0.44	0.05/0.48/-2.15	2.01/0.68/-5.15	0.98/0.93/+0.87

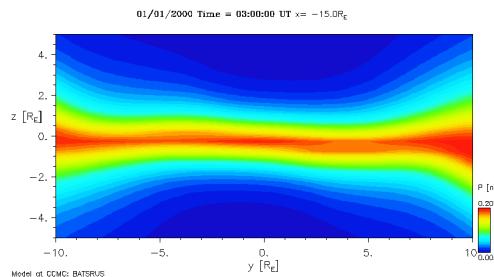
Summary of model performance



Lobe magnetic field



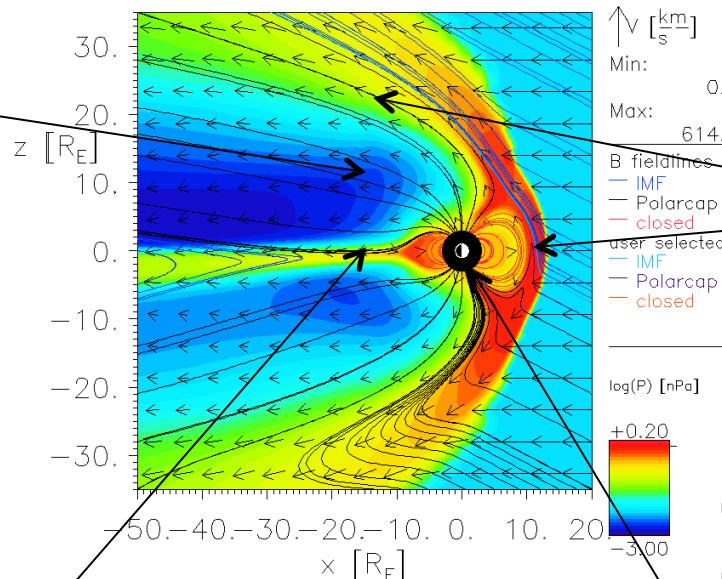
Growth phase



PS plasma pressure



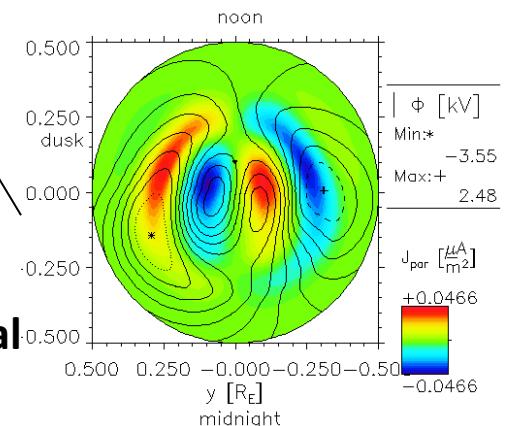
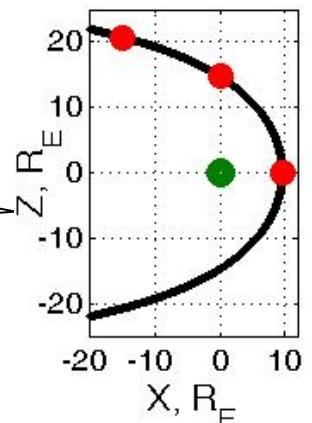
Longton GIF Animator unregistered [Longton Software Inc. http://www.longton.com]
01/01/2000 Time = 00:00:00 UT $y = 0.00R_E$



Field aligned currents & Cross polar cap potential



Magnetopause position



Summary

- **new approach to the validation and benchmarking** of the global MHD magnetospheric models ;
show the first systematic evaluation of four first-principle based global magnetospheric models
 - BATSRUS, LFM, GUMICS and Open GGCM; no one is a single leader; any code shows a systematic deviation from empirical results in some parameters used in validation.
- **evaluate quantitatively** the capability of global MHD models to represent **the key global-scale magnetospheric characteristics** related to:
 - global state (R_{MP} , P_{PS} , B_L)
 - magnetosphere – ionosphere connection (TFAC)
 - global magnetospheric dynamics (convection, growth phase)
- all GMHD models provide **reasonable match to global parameters characterizing GLOBAL EQUILIBRIA** in outer magnetosphere and their variations
Gordeev et al., 2015, Space Weather
- GMHD models show systematic differences in their DYNAMICAL RESPONSE , needs further investigation.